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Results from CMS on Higgs boson physics

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Results from CMS on Higgs boson physics

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Abstract. A selection of measurements and results of Higgs physics obtained by the CMS experiment are presented, obtained with proton collision data collected in 2015 and 2016 at the center-of-mass energy of 13 TeV.

1. Introduction

After over forty years of search efforts, the Higgs boson has been discovered by the CMS and ATLAS collaborations during the first extended running period of the CERN LHC (Run 1) with proton collisions at 7 and 8 TeV. The Run 1 data also served to measure and set constraints on many accessible properties as the Higgs boson mass, its production and decay rates and its couplings to other standard model (SM) particles.

In this document a minimal summary of Run 1 results from the CMS experiment [1] is given, followed by a review of preliminary results obtained with Run 2 proton collision data at 13 TeV. While the Run 1 data comprised a total integrated luminosity of about 25 fb^{-1} , the preliminary results presented here with Run 2 data are obtained with integrated luminosities of $2.3\text{--}2.7 \text{ fb}^{-1}$ collected in 2015, and $12\text{--}13 \text{ fb}^{-1}$ collected in 2016. It is to be noted that given the approximate twofold increase of signal and background cross sections for Higgs boson analyses, between the Run 1 and Run 2 collision energies, the statistical precision of the Run 2 data presented here is roughly equal to the precision obtained with Run 1 data.

2. Summary of CMS results with Run 1 data

The final combined Run 1 results from CMS are published in Ref. [2] making use of proton-proton collisions data collected in 2011 and 2012 and corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and up to 19.7 fb^{-1} at 8 TeV. Using the results of the two photon ($\gamma\gamma$) and four lepton (4ℓ) decay channels the mass of the Higgs boson is determined to be $m_H = 125.02^{+0.26}_{-0.27} \text{ (stat.) } ^{+0.14}_{-0.15} \text{ (syst.) GeV}$.

The event yields obtained in the different analyses production and decay channels are consistent with those expected for a standard model Higgs boson with the measured mass. No significant deviations were found, with the largest one related to the top-quark pair associated production mechanism ($t\bar{t}H$), about 2.2 standard deviation higher than expectations, as visible in Fig. 1 (left). The excess in the $t\bar{t}H$ channel was driven by the measurements in the same-sign (SS) dilepton decay mode, aiming mostly at fully leptonic W-pair decays of the Higgs boson [3]. On the other hand, when including constraints from other channels through gluon and photon loop-induced interactions, the Higgs boson coupling to the top quark does not appear to deviate



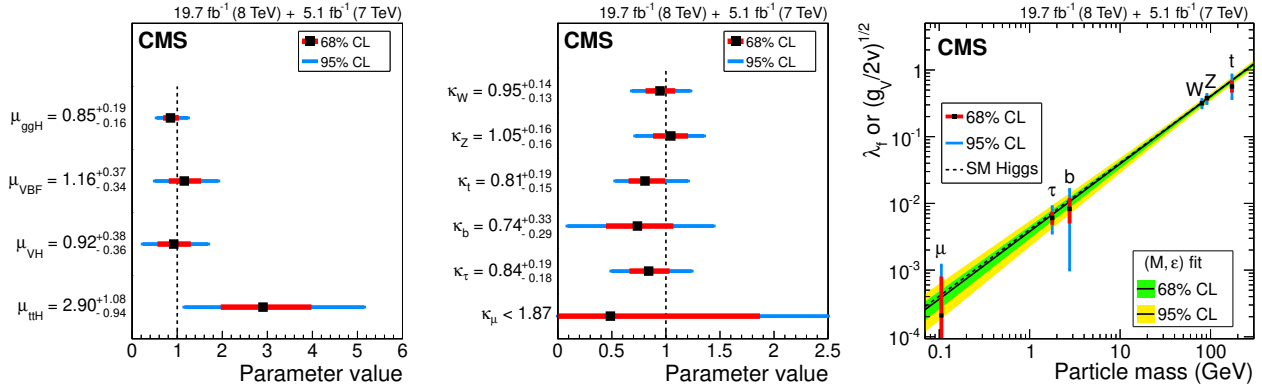


Figure 1. CMS Run 1 combined results [2]. Higgs boson production signal strengths relative to the SM expectations (left). Higgs boson couplings relative to the SM expectations (center), and versus the particle mass (right).

from the SM expectations, as also visible in Fig. 1 (right). It is therefore important to verify the top-Yukawa coupling both directly and indirectly with the new Run 2 data.

The Run 2 data will furthermore be crucial to establish the Higgs boson couplings to the down-type sector b-quarks, and to muons in the second fermion family.

3. Top-associated productions

3.1. With decays to b-quarks

First CMS results of the search for the associated production of a Higgs boson with a top quark-antiquark pair, decaying into a bottom quark-antiquark pair with 2016 Run 2 data have been recently released [4], and are shown in Fig. 2.

Events are split into several categories according to their expected signal purity. In each category the signal presence is measured using a multivariate approach that combines a matrix element method (MEM) with boosted decision trees (BDT). The $t\bar{t}H$ production cross section relative to the SM expectation is fitted to $\mu = -0.19^{+0.45}_{-0.44}(\text{stat.})^{+0.66}_{-0.68}(\text{syst.})$, that is compatible with SM expectations at the level of 1.5 standard deviations.

Results obtained with 2.7 fb⁻¹ of 2015 data, also at 13 TeV, yielded a fitted $\mu = -2.0 \pm 1.8$ [5]. Previous results with Run 1 data yielded $\mu = 0.7 \pm 1.8$ with a BDT method [3], and $\mu = 1.2^{+1.6}_{-1.5}$ with a MEM method [6].

3.2. With decays to leptons

The $t\bar{t}H$ search with leptons [7] selects events with two same charge sign (SS) leptons or at least three charged (3L) leptons, produced together with b jets. After the selection of events based on the expected signal topology, two BDT classifiers are trained to separate the signal from the main $t\bar{t}W$ and $t\bar{t}Z$ backgrounds. The outputs of the two BDT classifiers in each event category are combined in bins of different signal purity, shown in Fig. 3, and the signal contribution is extracted with a simultaneous fit of the all bins contents. The results are combined with the 2015 dataset and yield a $t\bar{t}H$ signal strength of $\mu = 2.0^{+0.8}_{-0.7}$ relative to the SM prediction. Results separated by event category and lepton flavour are shown in Fig. 3.

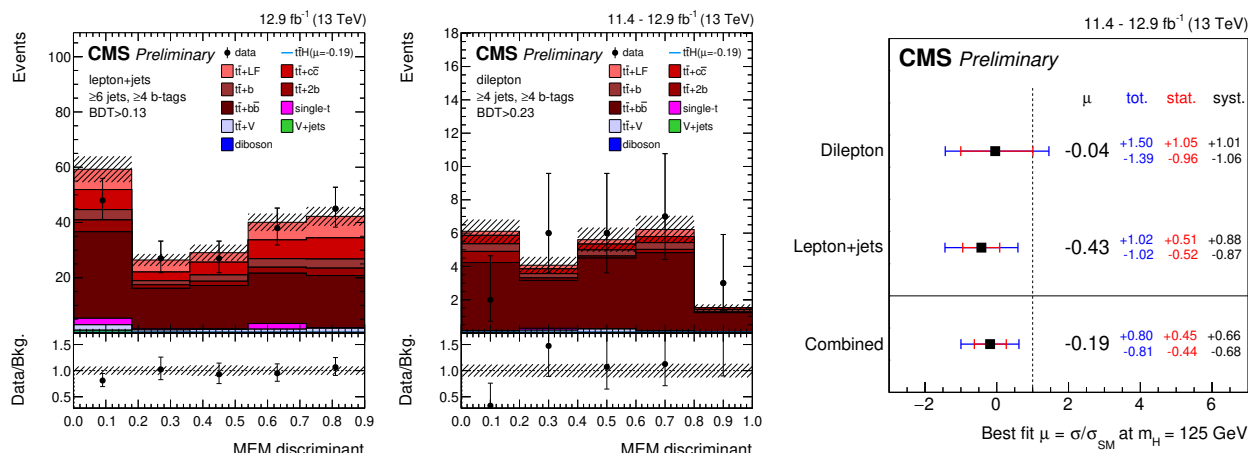


Figure 2. Preliminary Run 2 results in the top-pair associated production channel, with Higgs boson decays to b-quarks [4]. Final discriminant shapes (MEM) in the most signal-sensitive analysis categories for lepton+jets (left), and dilepton (center) events. Fitted values of the signal strength split per channel and into their statistical and systematic components (right).

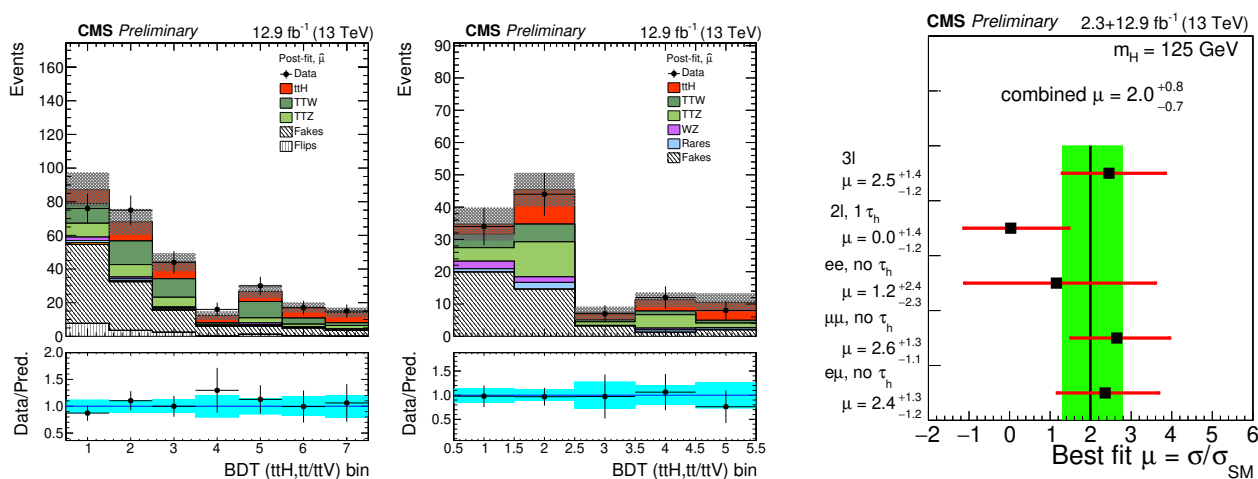


Figure 3. Preliminary Run 2 results in the top-pair associated production channel, with Higgs boson decays to leptons [7]. Combination of the BDT classifier outputs in the bins used for signal extraction, for the same-sign dilepton (left) and three-lepton (center) channels. Fitted signal strengths for the combined 2015 and 2016 data, for trileptons, dileptons and split into flavor categories (right).

3.3. With decays to photons

The search for $t\bar{t}H$ with photons [8] selects events with two photons, at least one b-jet, and additional jets or isolated leptons, defining hadronic and leptonic categories. The combined fit to the diphoton mass spectrum with 2016 data yields a signal strength of $\mu = 1.9^{+1.5}_{-1.2}$ relative to the SM prediction.

4. Two photon decays

The preliminary measurements of Higgs boson diphoton decays in different production processes with Run 2 data [8] follows closely the Run 1 strategy, with events divided into eight classes. The fitted signal strength with $m_H = 125.09$ GeV, is reported to be $\mu = 0.91 \pm 0.20$ relative to the SM prediction, corresponding to a significance of 5.6 standard deviations. A fiducial region is defined with generator-level requirements, and the fiducial cross section is measured to be 69^{+18}_{-22} fb compared to the 73.8 ± 3.8 fb theoretical prediction.

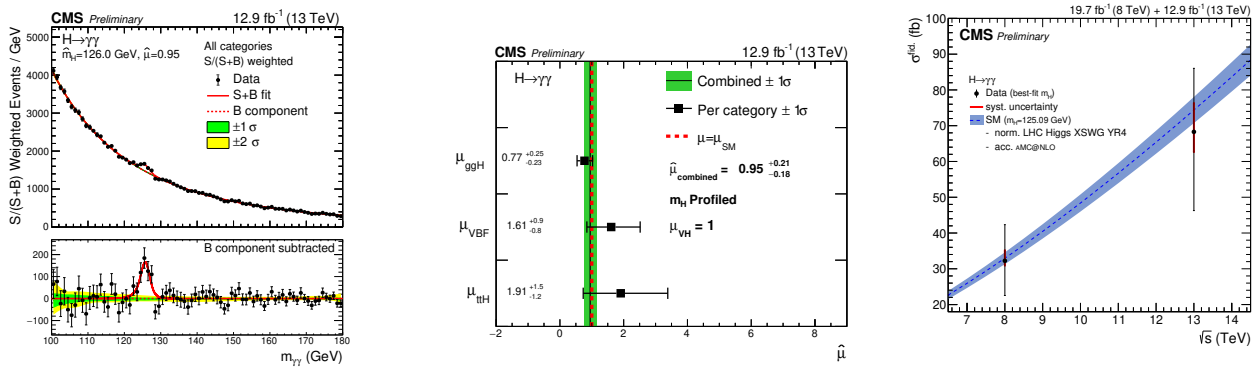


Figure 4. Preliminary Run 2 results with Higgs boson decays to photons [8]. Data points and signal plus background model fits of the diphoton invariant mass for all event categories summed and weighted by their sensitivity (left). Fitted signal strengths for each production process (center). Measurements of the fiducial cross section at 8 TeV and at 13 TeV (right).

5. Four lepton decays

Higgs boson decays to four-leptons (4ℓ) are selected with two pairs of opposite-sign, same-flavor isolated leptons. The analysis with 2016 data [9], makes use of new vector boson fusion (VBF), V-associated (VH) and $t\bar{t}H$ event categories with additional jets and leptons, and kinematic discriminants D are built in each event category.

The inclusive distribution of the 4ℓ invariant mass is shown in Fig. 5, where about 20 signal events are expected. Signal strengths are obtained with likelihood fits of $m_{4\ell}$ and D in 18 event categories. Results for different production channels are also shown in Fig. 5 for $m_H = 125.09$ GeV, with the final combined signal strength of $0.99^{+0.33}_{-0.26}$ relative to the SM prediction, corresponding to a significance of 6.2 standard deviations. A fiducial region is defined with generator-level requirements, and the cross section is measured to be $2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{syst.})^{+0.01}_{-0.05}(\text{model})$ fb compared to the theoretical prediction of 2.53 ± 0.13 fb. The energy dependence of the $H \rightarrow 4\ell$ fiducial cross section is shown in Fig. 5.

The Higgs boson mass in the 4ℓ channel is also extracted with likelihood scans shown in Fig. 6, leading to the nominal result $m_H = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{syst.})$ GeV. The Higgs boson width can be constrained by the off-shell production, fitting the 4ℓ mass distribution in the

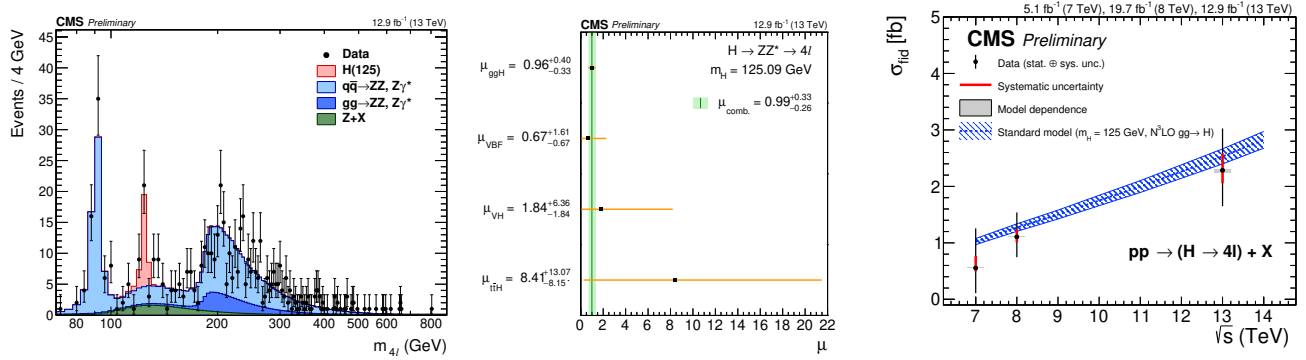


Figure 5. Preliminary Run 2 results with Higgs boson decays to four leptons [9]. Distribution of the four-lepton reconstructed invariant mass. Points represent the data and stacked histograms represent expected distributions with a 125 GeV Higgs boson (left). Fitted signal strengths for different production processes (center). The measured fiducial cross section as a function of \sqrt{s} (right).

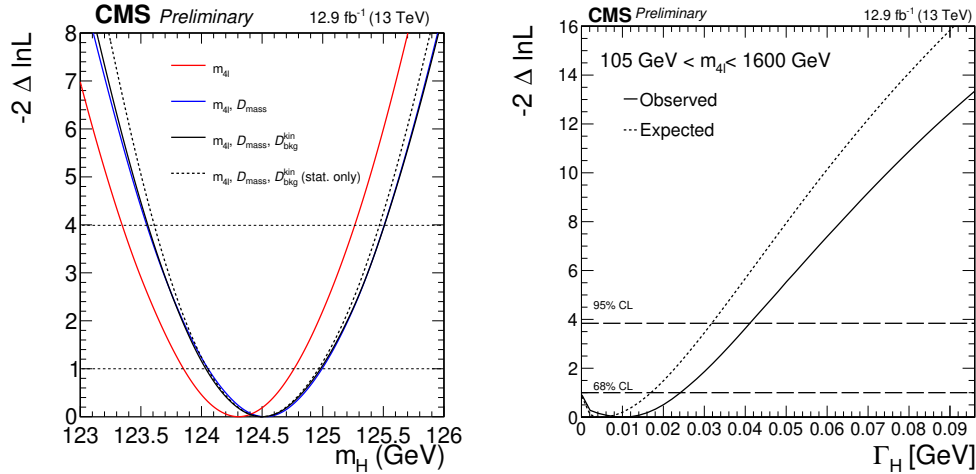


Figure 6. Preliminary Run 2 results with Higgs boson decays to four leptons [9]. Likelihood scan of the Higgs boson mass (left). Observed and expected likelihood scan of the Higgs boson width using the full four lepton mass range (right).

100-1500 GeV range, the resulting observed (expected) 95% confidence level (CL) upper limits are 41(32) MeV, as also shown in Fig. 6.

6. Higgs pair searches

6.1. Non-resonant HH

The production of Higgs bosons pairs allows to determine the self-coupling and the details of the SM Higgs potential. The Higgs boson pair production cross section predicted by the SM in 13 TeV proton collisions and for $m_H = 125$ GeV is about 33 fb. A search for non-resonant Higgs boson pair production with both Higgs bosons decaying into b-quark pairs has been

performed with 2.3 fb^{-1} of 13 TeV collision data collected in 2015 [10]. Events are collected by an hadronic multijet trigger with online b-tagging, and selected offline with a BDT classifier. The two-dimensional distribution of reconstructed dijet masses is fitted to search for the signal presence, as shown in Fig 7, and no excess over the data-driven predicted background is found. The resulting observed (expected) 95% CL upper limits are 3880(3490) fb, corresponding to 342(308) times the SM prediction.

The non-resonant Higgs boson pair production has been also searched for in the $bb\tau\tau$ final state with 12.9 fb^{-1} of 13 TeV collision data collected in 2016 [11]. No excess is found over the background expectations and the resulting observed (expected) 95% CL upper limits are 508(420) fb, corresponding to 200(170) times the SM prediction.

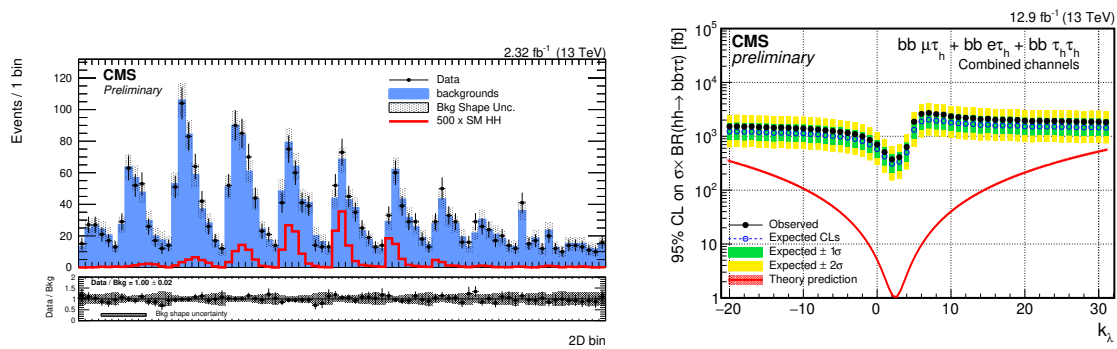


Figure 7. Preliminary Run 2 results of non-resonant Higgs boson pair productions [10, 11]. Background-only fit of the 2D dijet mass plane for the search in the four b-jet channel (left). Observed and expected 95% CL upper limits on HH cross section times branching ratio in the $bb\tau\tau$ channel, as a function of the trilinear coupling κ_λ relative to the SM prediction (right).

6.2. Resonant HH

Searches for narrow-width resonances decaying into two Higgs bosons have been performed in the $bbbb$ [12], $bb\tau\tau$ [13], $bb\gamma\gamma$ [14], and $bbWW$ [15] final states, using 2015 and 2016 proton collision data. No evidence for a signal is observed in any of the searched final states and upper limits at a 95% CL are set on the resonance production cross section, in the mass range from 260 to beyond 1 TeV are set, as shown in Fig. 8.

7. Future prospects

Updates on projections of physics reach with the upgraded CMS detector for high luminosity LHC have been recently released [16], taking into account the effects of high pileup conditions and expected detector performances. The extrapolated results are given for dataset of 300 fb^{-1} and 3000 fb^{-1} in two more or less conservative scenarios for systematic uncertainties. The effects of higher pileup conditions and detector upgrades are taken into account for the 3000 fb^{-1} projections.

The updated projections for the diphoton and four lepton decay channels are shown in Fig. 9. Most sensitivity projections are statistically limited, and scale roughly with $1/\sqrt{\mathcal{L}}$ up to 300 fb^{-1} with the potential of reaching a precision three to four times better than what was obtained with the Run1 data. Systematic limitations become important in many sensitivity projections with 3000 fb^{-1} , when the precision could reach 5-10 times the Run 1 sensitivity levels.

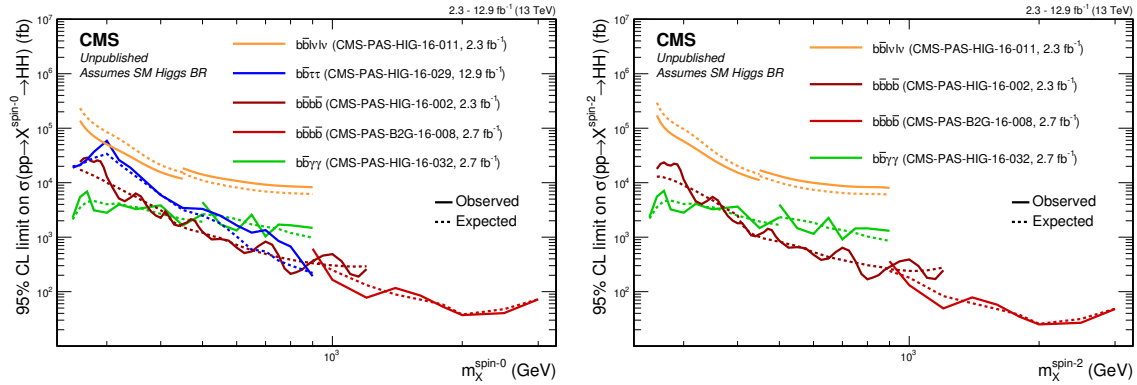


Figure 8. Preliminary Run 2 results for resonant pair productions of Higgs bosons [12, 13, 14, 15]. Observed and expected 95% CL upper limits on the resonant HH cross section as a function of the resonance mass in the spin-0 (left) and spin-2 (right) hypotheses.

8. Summary

Results with the first $2.7+12.9 \text{ fb}^{-1}$ of 13 TeV proton collisions data have been produced by the CMS experiment, leading to the rediscovery of the Higgs boson with significances in excess of five standard deviations both in the diphoton and four-lepton channels. The new data did not reveal any significant deviations from the SM, any additional Higgs bosons, nor di-higgs productions, yet. Higgs boson physics at CMS is gradually evolving from discovery to higher precision measurements, looking forward to establish the coupling to down-type quarks, through b-jets decays, and then the coupling to the second generation, through dimuon decays. Exciting prospects are ahead of us with the full Run 2 data and beyond.

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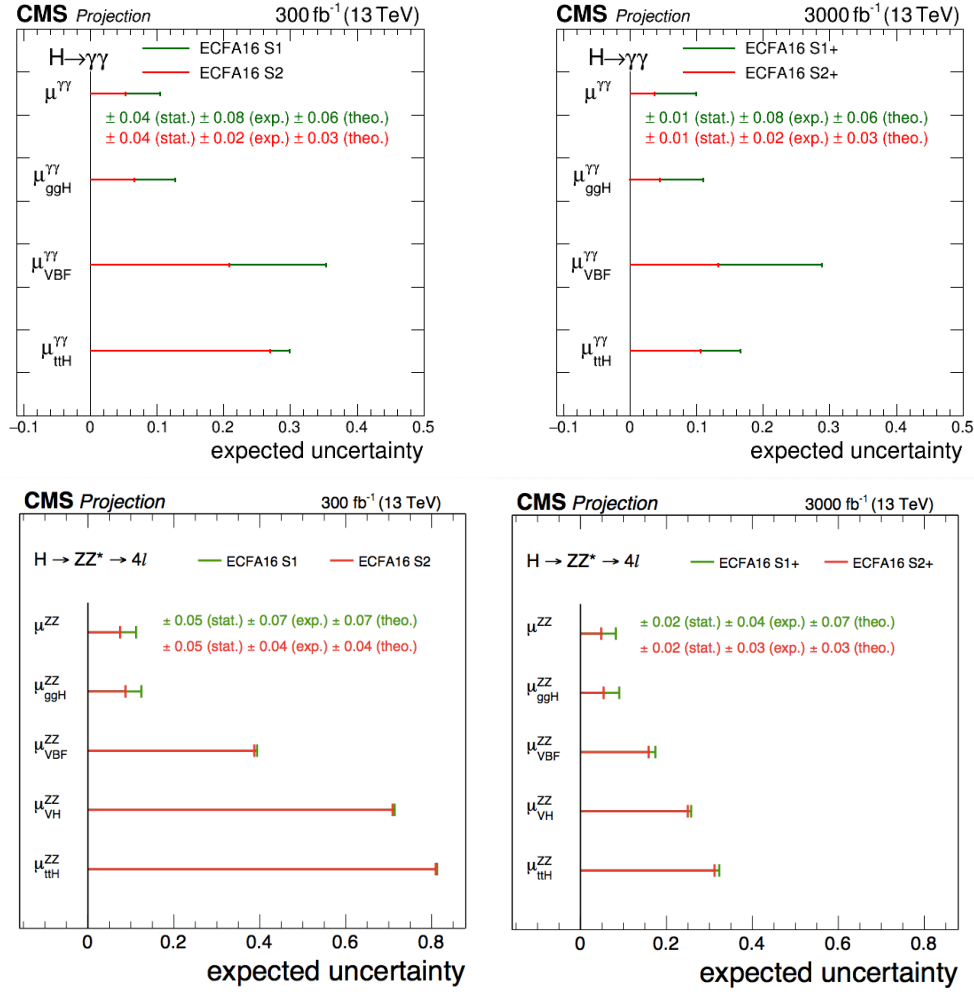


Figure 9. Projected 68% CL uncertainties on the Higgs boson productions [16] with decays to diphotons (top) and four leptons (bottom), with 300 fb⁻¹ (left) and 3000 fb⁻¹ (right) under the two different scenarios described in the text.

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